Energy Conversion and Management 64 (2012) 170–181

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

The effects of window alternatives on energy efficiency and building economy in high-rise residential buildings in moderate to humid climates

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ARTICLE INFO

Article history:
Received 3 February 2010
Received in revised form 30 April 2012
Accepted 23 May 2012
Available online 24 September 2012

Keywords:
Energy efficiency
Heating load
Cooling load
Life cycle cost
Double glazing window
Energy simulation software

ABSTRACT

Currently, focused efforts are being made to determine the influence of windows on the energy consumption and economy of high-rise buildings. Certain window designs and appropriate glazing systems reduce building energy consumption for heating and cooling and contribute to building economy. This paper addresses double-glazed window units that are composed of tinted glass; clear reflective glass; low emissivity (low-e) glass; and smart glass (one surface consists of a high-performance, heat-reflective glass, and other surface has a low-emissivity coated). These materials reduce the heating and cooling loads of buildings by providing solar control and heat conservation. The aim of this study was to investigate the effects of these alternative units, rather than readily available double-glazed units, in two types of flats. The flats have the same construction and operating system, but they have different plan types with regard to building energy consumption and building economy as it relates to life cycle cost analysis. For this study, we selected buildings in Trabzon, in Climate Region II of Turkey, due to its moderate-humid climate. F- and C-type high-rise residential blocks, with flats composed of two to three bedrooms, constructed by the Republic of Turkey's Prime Ministry Housing Development Administration of Turkey (TOKİ) are used as models for the simulation. The flat plans in these blocks are modeled using DesignBuilder v.1.8 energy simulation software. The simulation results show that smart-glazed units and those with low emissivity glazing are the most efficient alternatives with regard to building energy consumption and economy.

1. Introduction

When developments in technology and industry, population growth, energy, and increased construction costs are considered, it is observed that the ratio of production to consumption has decreased dramatically worldwide. According to one study, US and UK citizens consume 80 and 45.8 kW h of energy per person per annum, compared with an average of 36.4 kW h per capita in Europe [1]. Over the past two decades, in Turkey and in other countries, energy demand has rapidly risen, thereby increasing energy demand and imports. From 2002 to 2007, while energy demand grew at a rate of 6.9%, energy imports increased by 31% per year. As a result, Turkey imported approximately 74% of its total energy demand in 2007. According to the Ministry of Energy and Natural Resources, approximately 80% of the total energy demand will be imported by 2030. As increasing energy demand and energy imports are reconsidered annually, it is certain that our country's economy of energy income will be substantially high by 2030 [2,3].

Due to this increase in energy income, as well as to the issues of global warming and environmental pollution, energy efficiency is considered to be of primary importance in the industry, transportation, agriculture and residential sectors in Turkey. Currently, the country's residential sector comprises 30–40% of its total energy consumption [4]. Given this statistic, measures to reduce the heating and cooling loads of residential buildings, as well as the use of passive systems, are important in the design of energy-efficient houses. Consequently, building authorities, such as architects, engineers, and owners, should implement innovations and identify methods with which to reduce energy consumption in homes.

Recently, the number of studies on reducing energy consumption for heating and cooling in buildings has considerably increased [5–37]. In most of these studies, the effects of different parameters (e.g., wall construction, window-wall ratio, window type, climate, orientation, solar control devices, HVAC equipment, and lighting) on the heating and cooling load of existing and/or hypothetical building models were tested using energy simulation software (DOE – 2.1 [21,23,26], TRNSYS [17,19,22,34], EnergyPlus [24,29,36,37], HTB2 [20,28], and Energy-Win [30]), simple equations, and manual calculations based on norms and simple software [18,25,27,32,33,35]. On the basis of these norms the most appropriate energy-saving alternatives were determined. In addition to building energy simulations [17–37], several studies were performed, including those concerning economic analyses

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http://dx.doi.org/10.1016/j.enconman.2012.05.023

Nomenclature

A	area (m^2)
d	thickness (m)
e	emissivity (dimensionless)
h	surface heat transfer coefficient (W/m^2 K)
H	height (m)
L	weight (m)
q	heat flux (W/m^2)
R	reflectance (dimensionless)
SHGC	solar heat gain coefficient (dimensionless)
T	transmittance (dimensionless)
U	heat transmittance coefficient (W/m^2 K)
Greek symbols	
α	absorptivity (dimensionless)
λ	thermal conductivity (W/mK)
Subscripts	
ext	exterior
int	interior
j	surface
g	glass
θ	time
sol	solar
vis	visible
Abbreviations	
CLR	6 mm clear + 12 mm air space + 6 mm clear
HABLU	6 mm blue + 12 mm air space + 6 mm clear
HAGRN	6 mm green + 12 mm air space + 6 mm clear
HRBLULE2	6 mm blue HRG (low-e #2) + 12 mm air space + 6 mm clear
HRCLR	6 mm clear HRG + 12 mm air space + 6 mm clear
HRGRNLE2	6 mm green HRG (low-e #2) + 12 mm air space + 6 mm clear
I	initial capital investment (TL)
IV	interior ventilation gap
LECLR3	6 mm clear + 12 mm air space + 6 mm low-e#3
LECLR2	6 mm low-e #2 + 12 mm air space + 6 mm clear
LCC	life cycle cost
M.R.O	maintenance-repair-operation cost (TL)
R	replacement cost (TL)
RV	residual value (TL)

of buildings [26,27,29,37]. Among these studies, reducing the heating and cooling load with energy-efficient windows is a topic of great importance [25–37]. The production of solar control glasses (absorbing, reflective), heat conservation glasses (low-e coated), and solar control and heat conservation glasses (reflective and low-e coated) has become widespread, and the manner in which energy savings are provided by the use of these glasses in buildings is the central topic in many of these studies. Weir and Muneer [25] investigated the effects of the use of four main gases in the construction of inert gas-filled, double glazed units on the energy performance of windows. Following this study, Sekhar and Toon [26] determined the energy consumption of many different double glazed units (heat conservation, solar control, and heat conservation + solar control glasses) used in hypothetical building models. This evaluation was achieved through the use of energy simulation software and the performance of life cycle cost analysis of double glazed units. In contrast to Sekhar and Toon's study, Karlsson et al. [27] developed a simple method to calculate the energy consumptions of differently glazed units in various climates, as well as for various buildings and orientations, and conducted an economic analysis. Bojic et al. [28] used methods identical to those of Sekhar and Toon [26], but they investigated the effects of various glazed units on the energy consumption of two existing flats rather than implementing Sekhar and Toon's hypothetical building model. Bojic et al. [28] also did not perform an economic analysis. Çetiner and Özkan [29] suggested an approach for evaluating energy and economic efficiency using different single- and double-glazed facade configurations in a block with 30 stories using energy simulation software. Similar to Sekhar and Toon [26] and Bojic et al. [28], Stegou-Sagia et al. [30] determined the effects of differently glazed units (tinted and clear double glazed units) and the window-wall ratio on the energy consumption of existing residential and office buildings in two climate regions using energy simulation software. In the study, they also suggested appropriate alternatives for different climate regions. Considering the results of these previous studies, Gugliermetti and Bisegna [31] developed a reversible glass window in a double-glazed unit, in which one layer was absorptive and the other was clear. They found that double-glazed window systems composed of an absorbing pane and a clear glass pane could reduce yearly energy requirements if they were rotated by 180°; specifically, during the heating season, the absorbing pane should face the indoor side, while during the cooler season, the absorbing pane should face the outdoor side. Macka [32] and Yasar et al. [33] calculated the energy consumptions of numerous single-, double- and triple-glazed units for summer and winter conditions. They used self-developed software based on simple equations to determine thermal performance criteria of windows according to Turkish climate regions, and they suggested appropriate glazed units for each climate region. Urbikain and Sala [34] investigated methods of estimating energy savings through the use of various types of windows in residential buildings. Whereas Hassouneh et al. [35] used self-developed software based on simple equations to determine how different window types in residential buildings shape building energy consumption, Ebrahimpour and Maerefat [36] calculated building energy consumption with existing energy simulation software. Furthermore, Ebrahimpour and Maerefat [36] tested the effects of solar control devices on the energy consumption of windows. Maçka and Yasar [37] determined the energy performance of the same windows in cold climates, rather than moderate-humid climates, using the method described in the present study.

In this study, we used energy simulation software to determine the effects, including building energy consumption and economy, of different types of glazed units (solar control, heat conservation and solar control, and heat conservation glazed units) used in high-rise residential buildings located in moderate-humid climate regions of Turkey. The use of this software and the analysis of a larger number of double-glazed units enabled the performance of a comprehensive energy and economic study.

2. Methods

By using the DesignBuilder energy simulation software, this study adopted the energy consumption values of several glazed window units in two high-rise residential blocks in Trabzon. To investigate the effects of different glass types on the heating and cooling loads of buildings, all parameters, with the exception of the glazing units of the windows, were kept constant.

Subsequently, life cycle costs of each window alternative were calculated by summing the initial capital investment and the energy cost of the windows. Finally, the energy and economic efficiency of the glazing unit alternatives were assessed, and appropriate alternatives were determined for the flats.

2.1. Glass in buildings

Windows are a significant element of buildings in terms of their contribution energy efficiency and building economy. Therefore, the window design and appropriate glazing system need to be correctly selected [38]. Criteria such as the solar control and heat conservation performance of glass, building function, building orientation, window area, window location, and climatic factors strongly affect energy efficiency in window design. These criteria should be known so that designers can make the best possible selection [39].

2.1.1. Glass types

Instead of the available glass typically used in flats, we investigated low-e coated glass with emissivity values of 0.15 and 0.10 for surface numbers 2 and 3, respectively, facing the gap of the double-glazed unit; blue and green absorptive glass; clear reflective glass; blue, high-performance, low-e reflective coated glass; and green, high-performance, low-e reflective coated glass. The thermophysical–optical and dimensional properties of the single glasses used in the double-glazed units are given in Table 1. The thermal performance criteria of the double-glazed units composed of the single glasses in Table 1 are provided in Table 2 and were calculated using Win-Energy 1.0 software [32].

2.2. DesignBuilder energy simulation software

DesignBuilder v. 1.8.1 [40], a dynamic building energy simulation software, was used to determine the monthly and yearly heating and cooling loads in the flats of high-rise residential buildings in this study. This software is the first comprehensive user interface to use the EnergyPlus [41] dynamic thermal simulation engine developed by Lawrence Berkeley Laboratory (USA), which calculates the heating and cooling loads of buildings according to the ASHRAE heat balance method. This method ensures that all of the energy flows in each zone are balanced and involves the solution of a set of energy balance equations for the zone air, interior and exterior surfaces of each wall, roof, floor and window. These energy balance equations are combined with equations for transient conduction heat transfer through building elements, algorithms, and/or data on weather conditions, including outdoor air dry bulb temperature, wet bulb temperature, and solar radiation levels [42,43]. Energy balance equations for the exterior surfaces, interior surfaces, and zone air for each building element are shown below.

The following is a heat balance equation for the j exterior surface of the building element at time θ [42,43]:

$$q''_{conduction,ext,j,\theta} = q''_{solar,ext,j,\theta} + q''_{convection,ext,j,\theta} + q''_{radiation,ext,j,\theta} \quad (1)$$

Table 2
Thermal performance criteria of the double-glazed units used in the building simulation model [32].

Double-glazed unit (6–12–6 mm)	U (W/m^2 K)	SHGC	T_{SOL}	T_{VIS}
CLR	2.7	0.70	0.60	0.78
LECLR3	1.9	0.66	0.53	0.72
LECLR2	1.8	0.36	0.27	0.46
HABLU	2.7	0.38	0.24	0.37
HAGRN	2.7	0.40	0.27	0.58
HRCLR	2.7	0.45	0.37	0.34
HRBLULE2	2.7	0.32	0.19	0.34
HRGRNLE2	2.7	0.32	0.19	0.42

where $q''_{conduction,ext,j,\theta}$ is the conduction heat flux (W/m^2), $q''_{solar,ext,j,\theta}$ is the absorbed solar heat flux (W/m^2), $q''_{convection,ext,j,\theta}$ is the convection heat flux (W/m^2) and $q''_{radiation,ext,j,\theta}$ is the thermal radiation heat flux (W/m^2).The heat balance equation for the j interior surface of the building element at time θ [42,43] is as follows:

$$q''_{conduction,int,j,\theta} + q''_{solar,int,j,\theta} = q''_{convection,int,j,\theta} + q''_{radiation,int,j,\theta} \quad (2)$$

where $q''_{conduction,int,j,\theta}$ is the conduction heat flux (W/m^2), $q''_{solar,int,j,\theta}$ is the absorbed solar heat flux (W/m^2), $q''_{convection,int,j,\theta}$ is the convection heat flux (W/m^2) and $q''_{radiation,int,j,\theta}$ is the thermal radiation heat flux (W/m^2).

The heat balance equation for the zone air [42,43] is:

$$\sum_{j=1}^{N} A_j q''_{conduction,int,j,\theta} + q''_{inf,\theta} + q''_{system,\theta} + q''_{int,conv,\theta} = 0 \quad (3)$$

where A_j is the area of the jth surface (m^2), $q''_{inf,\theta}$ is the heat gain due to infiltration (W), $q''_{system,\theta}$ is the heat gain due to the heating/cooling system (W), and $q''_{int,conv,\theta}$ is the convective portion of internal heat gains due to people, lights, or equipment (W).

As mentioned in the equations above, 8760 h are analyzed from one entire year by the energy simulation software. The obtained energy simulation results are presented monthly and yearly in tables and figures. In this study, the window results are presented because the effects of windows on building energy efficiency are investigated.

2.3. Meteorological data

The building model was located in Trabzon (39.72°N, 41°E, altitude 30 m), in Climate Region II, representing the moderate-humid climate of Turkey [44]. In Fig. 1, monthly, daily, and hourly variations in temperature are shown for Trabzon according to average hourly temperature data between 1996 and 2006 [44]. Meteorological data for Turkey's Climate Region II are given in Table 3.

2.4. Building model

F- and C-type high-rise residential blocks with eight and twelve stories, respectively, constructed by the Republic of Turkey Prime

Table 1
Thermophysical-optical and dimensional properties of single glasses [32].

Glass types	d (mm)	λ (W/mK)	T_{sol}	R_{sol1}	R_{sol2}	T_{vis}	R_{vis1}	R_{vis2}	e_1	e_2
S1. Clear glass	6	1	0.77	0.07	0.07	0.88	0.08	0.08	0.84	0.84
S2. Low-e glass (pyrolytic coated)#3	6	1	0.66	0.11	0.10	0.81	0.10	0.10	0.15	0.84
S3. Low-e glass (soft coated)#2	6	1	0.33	0.20	0.23	0.52	0.09	0.10	0.84	0.10
S4. Absorbtive glass (blue)	6	1	0.30	0.04	0.04	0.42	0.05	0.05	0.84	0.84
S5. Absorbtive glass (green)	6	1	0.33	0.04	0.04	0.66	0.06	0.06	0.84	0.84
S6. Reflective glass (clear)	6	1	0.49	0.27	0.20	0.37	0.34	0.26	0.84	0.84
S7. Smart glass (absorbtive + reflective + low-e-blue)	6	1	0.23	0.21	0.07	0.38	0.26	0.12	0.20	0.84
S8. Smart glass (absorbtive + reflective + low-e-green)	6	1	0.23	0.21	0.08	0.47	0.27	0.15	0.20	0.84

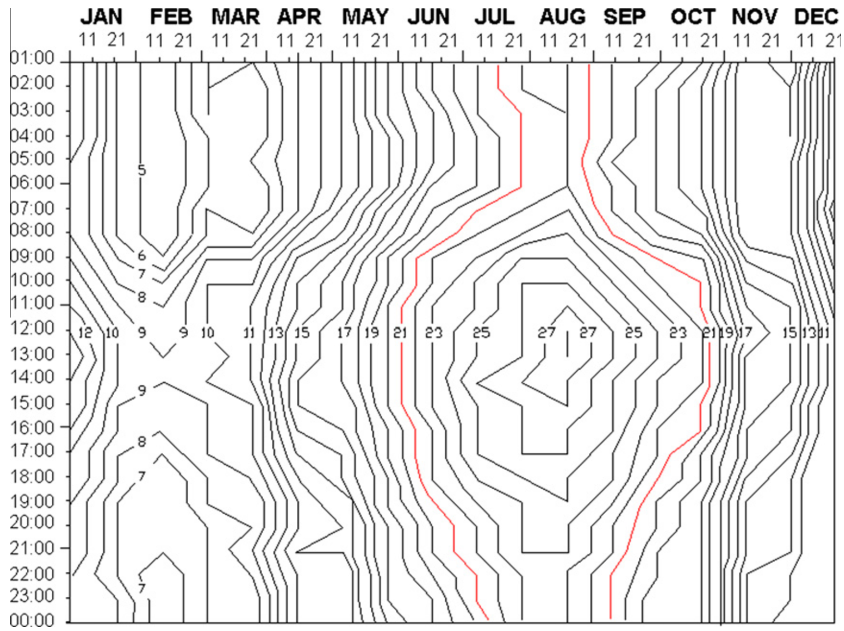

Fig. 1. Equal temperature curves of Trabzon [44].

Table 3
Meteorological data for Climate Region II [44].

	January	February	March	April	May	June	July	August	September	October	November	December
Outside dry bulb temperature (°C)	5.7	4.8	7.2	12.2	16.7	21.6	24.0	24.2	20.8	16.4	11.3	7.8
Dew-point temperature (°C)	2.3	−0.6	3.0	5.8	11.4	14.3	17.9	19.2	13.7	10.5	6.9	5.0
Wind speed (m^2/s)	4.7	5.4	4.1	4.1	4.3	3.9	5.7	5.6	4.9	4.2	4.0	5.5
Wind direction (°)	130.6	172.0	150.7	152.4	128.7	126.6	54.8	80.2	76.1	102.1	166.3	103.0
Atmospheric pressure (Pa)	101.9	101.2	101.4	100.7	101.1	100.9	100.7	101.0	101.1	101.2	101.5	101.0
Direct normal radiation (W/m^2)	39.7	30.2	40.7	70.7	104.3	132.0	158.8	135.2	117.6	65.0	38.9	21.2
Horizontal diffuse radiation (W/m^2)	32.1	42.5	68.1	82.8	96.5	95.0	85.8	80.6	63.0	53.8	36.4	30.5

Ministry Housing Development Administration (TOKİ) were used for the energy and cost efficiency analysis. The flat height is 2.8 m. The simulation study is based on the layout of Flat 1 of the F and C blocks. The flat in the F block has two bedrooms, and the flat in the C block has three bedrooms. These flats, with seven and eight thermal zones, respectively, face southeast. Flat 1 in the F block with a total floor area of 56.85 m^2, has two bedrooms, one living room, one bathroom, one toilet, and one kitchen; Flat 1 in the C block, with a total floor area of 99.42 m^2, has three bedrooms, one living room, one bathroom, one toilet, and one kitchen. There are different window orientations in the flats. For Flat 1 in the F block, 40% of the windows face north, 57% face south, and only 1.4% face southeast. For Flat 1 in the C block, 63% of the windows face south, and 34% face east. The room and window dimensions of the flats are given in Table 4. Figs. 2 and 3 show the modeled flats.

2.4.1. Building model construction

The compositions of the walls of both flats are the same. Each flat has both exterior and partition walls. The exterior walls consist of four layers of material: a 20-mm-thick plaster layer on each side, a 190-mm-thick brick layer, and a 50-mm-thick expanded polystyrene – EPS heat insulation (on the outer surface). The heat transmittance coefficient (U-value) of the exterior walls is 0.57 W/m^2 K. The partition walls consist of three layers of material: a 140-mm-thick brick layer and a 20-mm-thick plaster layer on each side. For all of the walls, the plaster layers are gypsum. The heat transmittance coefficient (U-value) of the partition walls is

Table 4
Room and window dimensions of the flats.

	Flat 1 (‘F’ type-two bedrooms)	Window dimensions and orientation				Flat 2 (‘C’ type -three bedrooms)	Window dimensions and orientation			
		L (m)	H (m)	Area (m^2)	Direction		L (m)	H (m)	Area (m^2)	Direction
Bedroom 1	10.45	1.3	1.3	1.69	N	12.15	1.4	1.35	1.89	S
Bedroom 2	9.60	1.3	1.3	1.69	N	10.40	1.4	1.35	1.89	E
Bedroom 3	–	–	–	–	–	14.20	1.4	1.35	1.89	E
Living room	15.84	2.4	1.3	3.12	S	27.86	2.4	1.35	3.24	S
Kitchen	7.48	1.2	1.3	1.56	S	8.80	1.3	1.35	1.75	S
Bathroom	3.36	0.2	0.6	0.12	S	5.70	0.2	0.6	0.12	İV
Toilet	1.98	0.2	0.6	0.12	E	3.55	0.2	0.6	0.12	IV
Hall	8.14	–	–	–	–	16.76	–	–	–	–
Total	56.85	–	–	8.3	–	99.42			10.9	

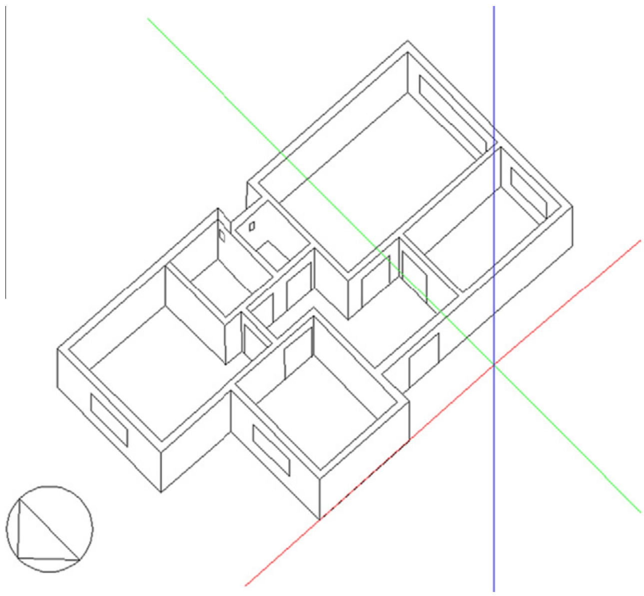

Fig. 2. F-type flat model [40].

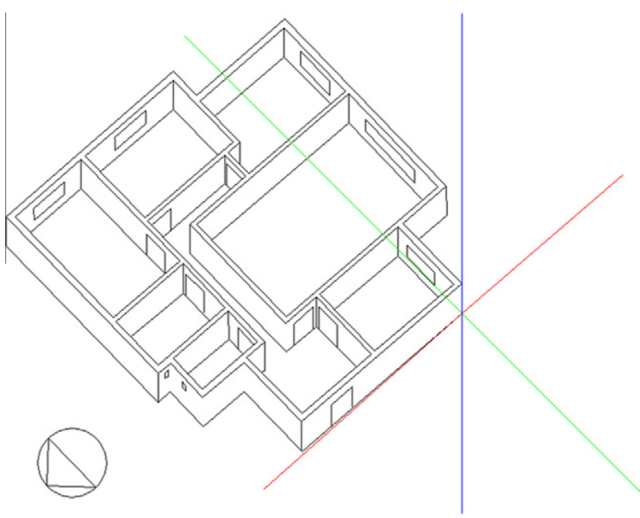

Fig. 3. C-type flat model [40].

2.01 W/m^2 K. The flat floors consist of four layers of material, listed from the lowest to highest surface: a 20-mm-thick gypsum plaster layer, a 140-mm-thick concrete layer, a 40-mm-thick morter, and a 20-mm-thick carpet/textile. The ceiling and floor constructions are the same, because the investigated flats are on intermediate floors. The heat transmittance coefficient (*U*-value) of the floor and ceiling construction is 1.34 W/m^2 K. The properties of the building materials used in the flats are given in Table 5.

The existing windows in the flats are composed of polyvinyl chloride (PVC) – 20 mm thick and 40 mm wide – and a double-glazed unit with two 6-mm-thick panes and a 12-mm-thick air gap [45]. In the double-glazed unit, a moisture-proof spacer with insulation is used. The heat transmittance coefficient (*U*-value) and shading coefficient (SC) of the double-glazed unit are 2.7 W/m^2 K and 0.81, respectively [32].

2.4.2. Utilization of model flats

Both flats were assumed to be the dwelling of a three-person family with two working adults and a studying child. Households generally use the flats in the evening and at night. Lights in the room were thought to be turned on or off during the daytime and evening in relation to the occupancy schedules, except for the bedrooms, where the lights would be turned on only in the evening. Except for the refrigerator, power devices consume energy only during the occupancy of the rooms.

Table 5
Properties of building materials used in the flats [40].

	Density (kg/m^3)	Specific heat capacity (J/kg K)	Thermal conductivity (W/mK)
Concrete	1800	1000	1.35
Gypsum plaster	1000	1000	0.40
Expanded polystyren – EPS	15	1400	0.04
Morter	2800	896	0.88
Brick	1700	800	0.84
Carpet	200	1300	0.06

The living room and all of the bedrooms in the flats are heated and cooled; the kitchen and bathroom are only heated, and the toilet and the common areas are not heated or cooled. The existing heating system in the flats is a central heating unit. Since natural gas is expected to be in use soon in Trabzon, it is assumed that the heating system of the flats will run on natural gas. The heating system is operated 6 months out of each year, from the beginning of October until the end of March, between 08:00 and 18:00. It is assumed that the cooling system in the flats is an air conditioner running on electricity. Heating and cooling set point temperatures are 18 °C and 22 °C, respectively. Bathrooms and toilets would be continuously naturally ventilated. The ventilation rates are assumed to be three air-changes per hour (achs).

2.5. Life cycle cost analysis

The life cycle costs include the total cost of ownership of machinery and equipment, including the cost of maintenance/repair, replacement, and operation; a summation of cost estimates, from inception to disposal, for both the equipment and operations; and an estimate of the total cost accrued annually for building life, as determined through an analytical study, with the time value of money also considered [46]. For the evaluation of a unit in terms of life cycle cost, all future costs during the unit life are discounted to the present value, with the exception of the initial capital investment of the project. The following formula is used to calculate the life cycle cost (LCC) [47]:

$$\mathrm{LCC} = \mathrm{I} + \mathrm{M.R.O} + \mathrm{R} - \mathrm{RV} \quad (4)$$

The parameters used in the LCC analysis are provided in Table 6.

2.5.1. Initial capital investment calculation

Square-meter unit prices of the double-glazed units in this study were obtained from the Republic of Turkey Ministry of Public Works and Settlement and from glass companies in Turkey. In accordance with the total glazing area in the flats, for each flat, a total of eight initial capital investments are calculated. While Table 7 shows the square-meter unit prices of the double-glazed units, Table 8 shows the total initial capital investment for the double-glazed units in the flats.

Data related to maintenance/repair and replacement are not presently available from the Republic of Turkey Ministry of Public Works and Settlement or from Turkish glass companies. Thus, these data are ignored in the LCCA, and only the initial capital investment and operation costs are used.

Table 6
Parameters used in the life cycle cost analysis.

Analysis type	General LCC analysis-non-federal, no taxes
Beginning date for LCC	2009
Study period	30 years
Planning/construction period	2 years
Service date	2011
Discount rate	15%
Life of glazing	60 years
Fuel type	Natural gas, electricity
The unit cost of natural gas	0.07368 TL/kW h (for 2009)
The unit cost of electricity	0.1983 TL/kW h (for 2009)

Current exchange rate; 1TL = US$0.6811.

Table 7
Cost of double-glazed units/m^2 (TL) [48,49].

Double-glazed unit type	Supply price/m^2 (TL)
CLR	55
LECLR3	63
LECLR2	62
HABLU	56
HAGRN	56
HRCLR	60
HRBLULE2	68
HRGRNLE2	68

2.5.2. Operation cost calculation

The operation costs of a building include total energy expenditures for heating and cooling of the building due to annual heat gains and losses and maintenance/repair costs in more specific periods. In this study, since there are not accurate data related to maintenance and repair costs, the energy expenditures are used for operation cost calculation. Since energy expenditures are paid regularly, these expenditures are updated by using a present worth analysis for a study period of 30 years, using a discount rate of 15% applied by the International Finance Association for projects in Turkey [50]. A yearly inflation rate of 12% is used for Turkey. In this method, the present value of energy expenditures is attained by multiplying the single present worth factor (SPW), which depends on the year, and the discount rate of 15% obtained from discount rate tables [50]. The yearly energy costs of the double-glazed units used in the study flats are given in Table 9.

3. Results and discussion

Until now, many researchers [26,28–31,34,36,37] have determined the effects of windows in differently glazed units with regard to their effect on building energy and economic efficiency in various climate regions (hot, moderate-humid, and cold) by means of energy simulation software. In these studies [26,28–31,34,36,37], the energy efficiency of differently glazed units was commonly analyzed according to the total annual energy load (heating and cooling load) obtained from simulation results. Although several studies [26,28,36,37] performed a cooling load analysis, only three studies [34,36,37] performed a heating load analysis in conjunction with a total annual energy load analysis. In the current study, we present monthly heat losses and gains of windows from investigated glazed units in conjunction with the total annual heating and cooling loads obtained from simulation results. The energy and economic efficiency of windows in two flats, in Trabzon's moderate-humid climate, are also discussed.

3.1. Comparing energy consumption through the different windows

The monthly heat gains/losses of the windows are shown in Figs. 4 and 5. The values in these figures are the mean monthly net energy flows through the windows, obtained by summing the heat gains/losses for each month from the simulation results.

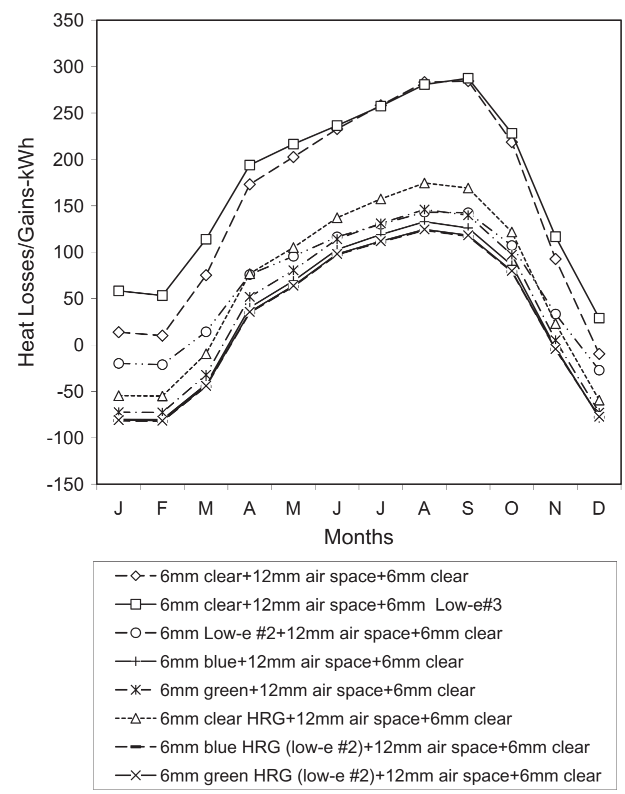

Fig. 4. Monthly total heat gains/losses through double-glazed units in the investigated flats in the F-type block – kW h.

Table 8
Total initial capital investment for double-glazed units used in the flats (TL).

	CLR	LECLR3	LECLR2	HABLU	HAGRN	HRCLR	HRBLULE2	HRGRNLE2
FLAT 1 (F type)	456.5	522.9	514.6	464.8	464.8	498	564.4	564.4
FLAT 1 (C type)	599.5	686.7	675.8	610.4	610.4	654	741.2	741.2

Table 9
Yearly energy costs of the double-glazed units used in the study flats – TL.

	CLR	LECLR3	LECLR2	HABLU	HAGRN	HRCLR	HRBLULE2	HRGRNLE2
Flat 1 – F type	254.86	247.76	133.14	131.63	142.40	165.10	123.96	124.84
Flat 2 – C type	422.87	410.41	221.75	220.90	238.50	275.28	205.06	206.89

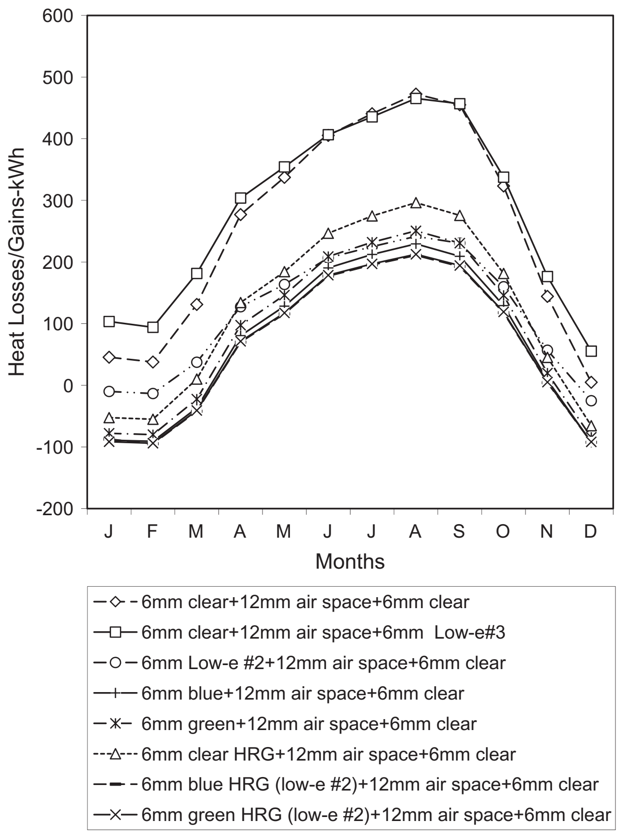

Fig. 5. Monthly total heat gains/losses through double-glazed units in the investigated flats in the C-type block – kW h.

Ebrahimpour and Maerefat [36] also considered net energy flows through the windows. The evaluations in the present study were performed by considering the heating period from the beginning of October until the end of March, with the cooling period extended from the beginning of April until the end of September.

As shown in Figs. 4 and 5, the most effective glazed units, in terms of reducing heat losses during the winter, are LECLR3, CLR, and LECLR2. Urbikain and Sala [34], as well as Ebrahimpour and Maerefat [36], found similar results in terms of heating energy consumption. Whereas Ebrahimpour and Maerefat [36] determined that LECLR3 was 57% more efficient than CLR, Urbikain and Sala [34] did not perform a percentage evaluation, and they found that using LECLR3 instead of CLR provided a heating energy savings of 22 kW h. In the present study, during the month of January, which is when the highest heat losses occur, LECLR3 provides 76.33% more energy savings than CLR. Numerically, three studies [34,36,this study] yielded different results. These differences are caused by the use of variable parameters, such as climate, window area, and building dimensions, as well as the use of different types of energy simulation software. The results of the present study demonstrated that HRCLR, HAGRN, HABLU, HRGRNLE2, and HRBLULE2 cause 63.65%, 72.58%, 75.25%, 75.48%, and 75.68% more heating energy consumption than LECLR2, respectively. Additionally, LECLR3 and CLR contribute 58.3 and 13.8 kW h to the heating energy consumption, respectively. Because the smart-glazed units (HRGRNLE2 and HRBLULE2) prevent the desired solar gains in winter due to their high solar control properties, they cause more heating energy consumption than CLR.

As shown in Figs. 4 and 5, the most effective glazing of units that reduced heat gains during the summer includes HRBLULE2, HRGRNLE2, HABLU, LECLR2, HAGRN, HRCLR, and LECLR3. Similarly, Sekhar and Toon [26] analyzed double glazed units, except for

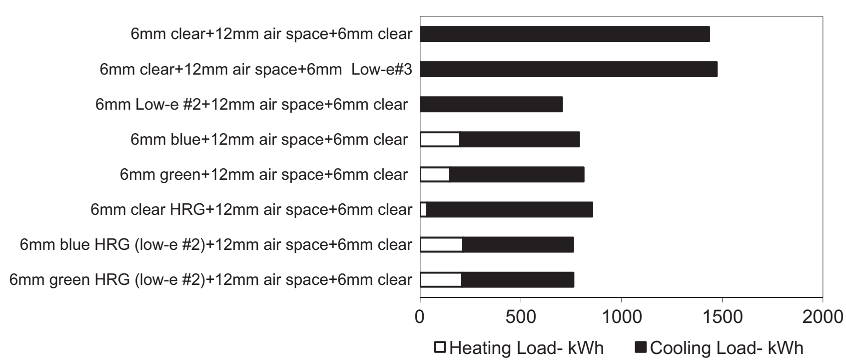

Fig. 6. Yearly heating and cooling loads of the double-glazed units used in the investigated flats in the F-type block – kW h/y.

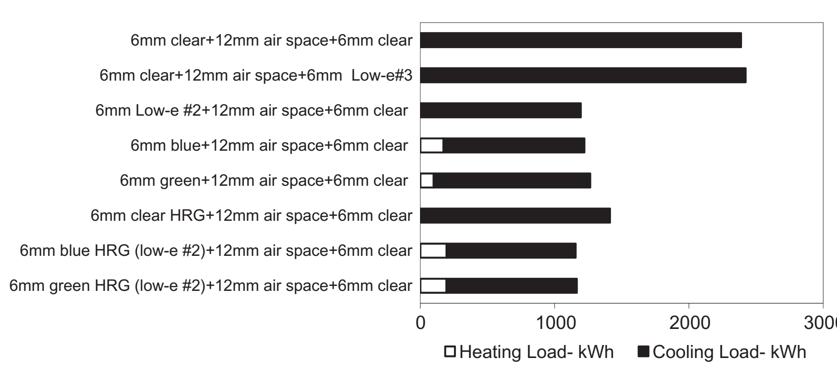

Fig. 7. Yearly heating and cooling loads of the double-glazed units used in the investigated flats in the C-type block – kW h/y.

Table 10
Energy consumption through the double-glazed units in the flats.

Double- glazed unit type	Flat 1 (56.85 m^2)			Flat 1 (99.42 m^2)		
	Total glazing area (m^2)	Yearly total energy consumption (kW h)	Net energy consumption for glazing area of 1 m^2 (kW h)	Total glazing area (m^2)	Yearly total energy consumption (kW h)	Net energy consumption for glazing area of 1 m^2 (kW h)
CLR		1033.42	124.50		1700.79	156.03
LECLR3		872.81	105.15		1473.71	135.20
LECLR2		617.12	74.35		989.04	90.73
HABLU		788.40	94.98		1221.80	112.09
HAGRN	8.3	810.99	97.70	10.9	1264.95	116.05
HRCLR		853.76	102.86		1348.22	123.68
HRBLULE2		758.79	91.42		1156.55	106.10
HRGRNLE2		760.46	91.62		1165.09	106.88

LECLR2 and LECLR3, with regard to cooling load, and obtained a similar order in terms of cooling energy efficiency. For example, in June (when the greatest heat gains occur), the glazed units of Flat 1 of the F block provide 57.08%, 56.69%, 53.93%, 49.66%, 49.25%, 39.05%, and 0.31% more cooling energy savings than CLR. The smart-glazed units (HRGRNLE2 and HRBLULE2) demonstrate higher solar control performances than the other units because they can absorb and reflect a large percentage of the solar radiation.

Annual heating and cooling loads are calculated using the total heat losses in the glazed units during the heating period, as well as the total heat gains in the glazed units during the cooling period. Figs. 6 and 7 show the annual heating and cooling loads of the glazed units used in the study flats.

In calculating life cycle costs of the glazed units, the heating–cooling energy costs based on studies of Sekhar and Toon [26], Çetiner and Özkan [29] and Hassouneh et al. [35] should be considered. Thus, Figs. 6 and 7 should be examined in terms of total energy consumption, including heating and cooling energy consumption. The fact that natural gas (used as the heating source) is less expensive than electricity (used as the cooling source) should be considered in the criteria.

In Figs. 6 and 7, it can be seen that LECLR2 (the unit with a low-e coating applied to surface two) and the smart glazed units

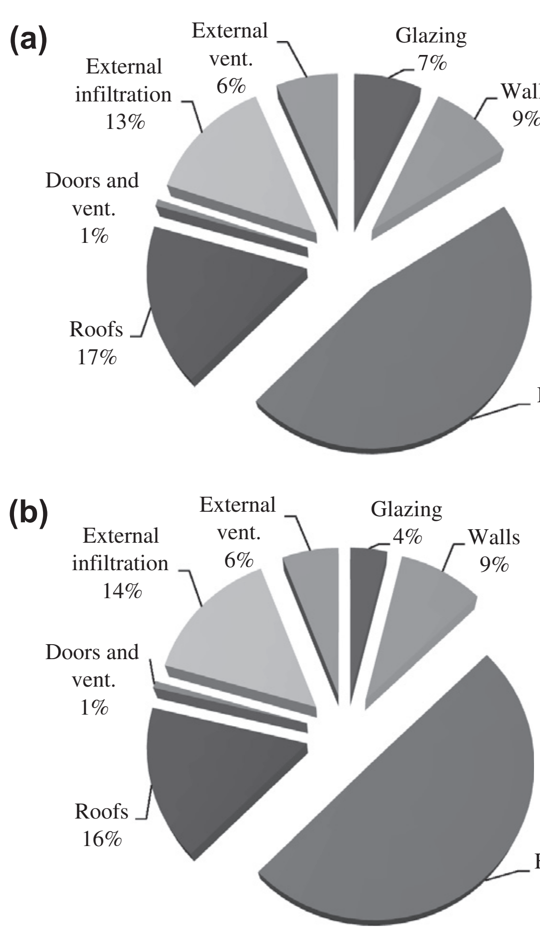

Fig. 8. Heat losses (%) through the building elements of the F-type blocks obtained from the simulation results – existing window-CLR (a), proposal window-LECLR2 (b).

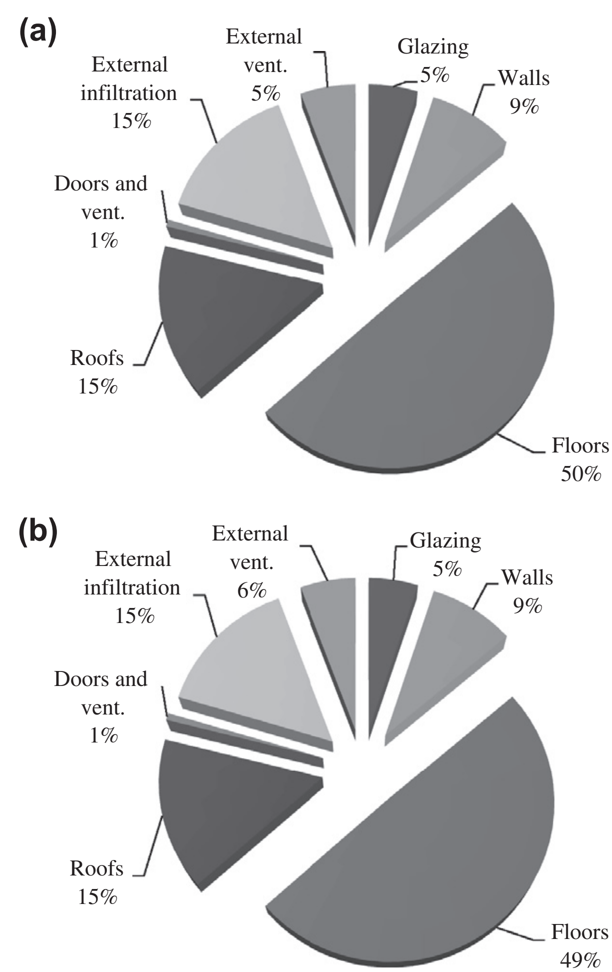

Fig. 9. Heat losses (%) through the building elements of the F-type blocks obtained from the simulation results – proposal windows-HRBLULE2 (a), HRGRNLE2 (b).

(HRGRNLE2 and HRBLULE2) are the most efficient in terms of total annual energy consumption (heating and cooling energy). Because Sekhar and Toons [26] did not investigate LECLR2, they found that smart-glazed units were the most efficient in terms of total annual energy consumption. As in this study, Karlsonn et al. [27] determined that LECLR2 was more energy efficient than heat absorptive (HABLU, HAGRN) and reflective (HRCLR) glazed units. In Flat 1 of the F block, LECLR2, HRBLULE2, HRGRNLE2, HABLU, HAGRN, HRCLR, and LECLR3 provide 416.3, 274.64, 272.96, 245.02, 222.43, 179.66, and 160.61 kW h more energy savings than CLR, respectively. In Flat 1 of the F block, LECLR3, CLR, and LECLR2 do not incur heating loads, as they contribute 599.28, 400.71 and 86.46 kW h to the heating energy during this heating period. In Flat 1 of the C block, LECLR3, CLR, LECLR2, and HRCLR do not incur heating loads, and they contribute 948.27, 686.99, 205.65, and 63.67 kW h to the heating energy during the heating period. Because the reflectance and absorption performances of LECLR2 (the unit with a low-e coating applied to a number of units with surface two in a double glazed unit) are inferior to those of the smart-glazed units, this unit also reduces heating loads. Although the cooling load of this glazed unit is higher than that of the smart glazed units, LECLR2 greatly reduces the heating load, such that the total energy consumption of these units is the lowest among the studied flats. Figs. 6 and 7 show only the heating and cooling loads for the glazed units, determined by calculating the total energy loads of these units. The heating energy savings provided by the glazed units not under heating loads are also considered.

3.1.1. Comparing energy consumptions through double-glazed units in the investigated flats

Table 10 shows that glazing area and total energy consumption are linearly proportional. Since the double-glazed units in the studied flats have different orientations, we cannot say that each double-glazed unit has the same linear proportionality.

3.2. Percentages (%) of heat gains and losses in Flat 1 of the F block

Heat losses occur through glazings, walls, floors, roofs, doors and ventilation, external infiltration, and external ventilation, while heat gains occur through general lighting, partitions, miscellaneous systems, occupancy, domestic hot water, heat generation, solar gains from exterior windows, lighting, and chillers. In Figs. 8 and 9, it can be seen that 7% of the total heat losses in the flat occur through the existing CLR window. In contrast, when LECLR2, HRBLULE2, and HRGRNLE2 are used, 3%, 2%, and 2% heating energy savings are provided, respectively.

Figs. 10 and 11 show that 14% of the total heat gain in the flat occurs through the existing CLR window. In contrast, when LECLR2, HRBLULE2, and HRGRNLE2 are used, 7%, 9%, and 9% cooling energy savings are provided, respectively.

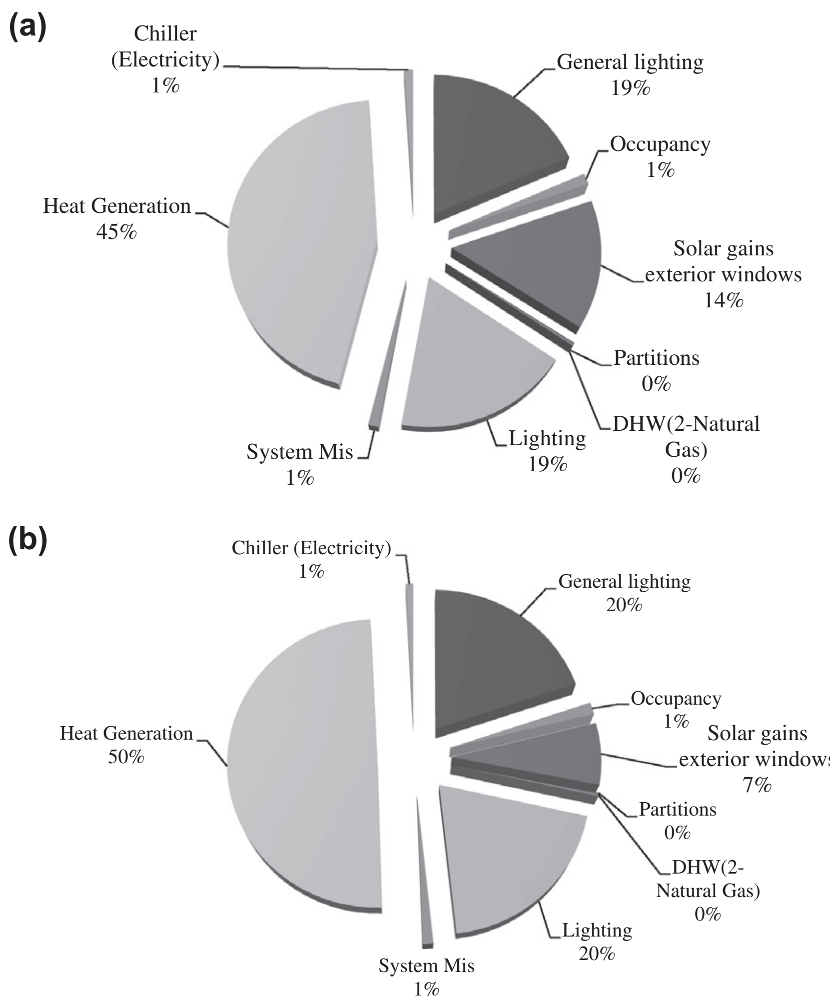

Fig. 10. Heat gains (%) in the F-type blocks obtained from the simulation results- existing window-CLR (a), proposal window-LECLR2 (b).

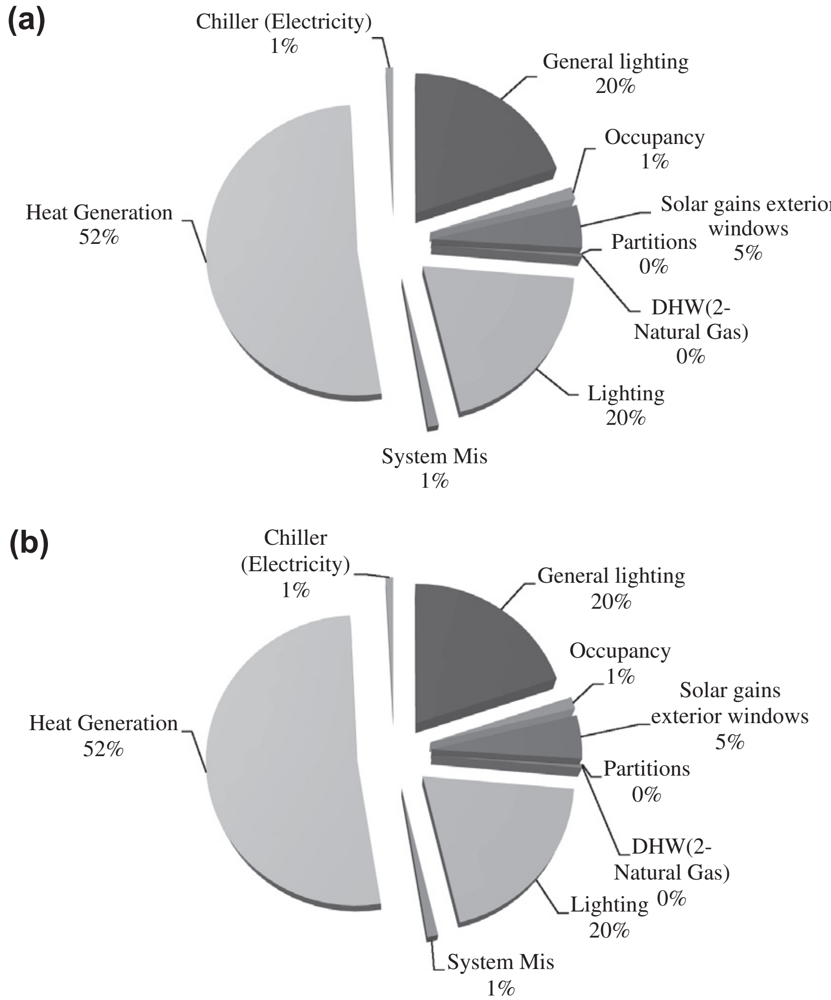

Fig. 11. Heat gains (%) in the F-type blocks obtained from the simulation results – proposal windows-HRBLULE2 (a), HRGRNLE2 (b).

3.3. Comparing the life cycle costs of glazing units

The fact that the lowest life cycle cost is the most economically efficient alternative for windows, based on the studies of Sekhar and Toons [26], Çetiner and Özkan [29] and Hassouneh et al. [35], was considered in the economic evaluation performed in the present study. As shown in Fig. 12, HRBLULE2, HRGRNLE2, HABLU, LECLR2, HAGRN, HRCLR, and LECLR3 provide 2277.46, 2261.37, 2237.38, 2159.92, 2041.11, 1594.24, and 63.04 TL more cost savings, respectively, than the CLR in Flat 1 of the F block. Due to the net energy savings of the HRBLULE2, HRGRNLE2, HABLU, and LECLR2 glazed units relative to CLR, the initial investment payback periods of these units are 3.6, 3.6, 3.2, and 3.6 years, respectively. As shown in Fig. 13, HRBLULE2, HRGRNLE2, HABLU, LECLR2, HAGRN, HRCLR, and LECLR3 provide 3827.58, 3794.25, 3669.65, 3588.83, 3348.94, 2635.11, and 140.02 TL more cost savings, respectively, than CLR. The payback periods of HRBLULE2, HRGRNLE2, HABLU, and LECLR2 are 3, 3, 2.7, and 2.9 years, respectively. As shown, LECLR3 is less economically efficient than CLR in the studied flats, as their payback periods are 20.1 and 17.9 years, respectively, for both flats.

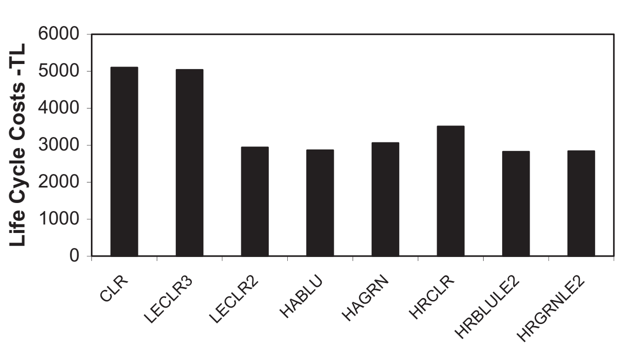

Fig. 12. Life cycle costs of the investigated double-glazed units in Flat 1, TL.

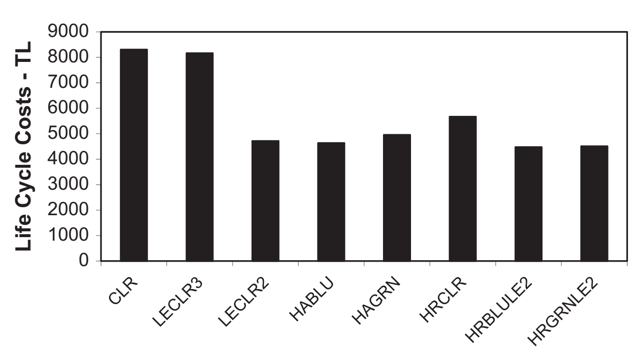

Fig. 13. Life cycle costs of the investigated double-glazed units in Flat 2, TL.

Table 11
A comparison of the energy efficiency, economy efficiency, and payback period of the investigated double-glazed units.

Double-glazed unit	Energy efficient performance	Economy efficient performance	Payback period
CLR*	●●●●●●●●	●●●●●●●●	●●●●●●●
LECLR3	●●●●●●●	●●●●●●●	●●●●●●
LECLR2	●	●●●●	●●●
HABLU	●●●●	●●●	●
HAGRN	●●●●●	●●●●●	●●
HRCLR	●●●●●●	●●●●●●	●●●●●
HRBLULE2	●●	●	●●●●
HRGRNLE2	●●●	●●	●●●●

* Reference double-glazed unit (●) the best performance, (●●●●●●●●) the poorest performance.

4. Conclusions

In this study, the energy and economic efficiency of eight double-glazed units with clear (existing glazing unit), low-e coated, tinted (blue, green), clear reflective, blue reflective + low-e coated, and green reflective + low-e coated were used in model flats and were evaluated according to simulation results for moderate/humid climates. In light of the simulation results, Table 11 shows the energy efficiency, economic efficiency, and payback period of the investigated double-glazed units.

We can make the following conclusions.

- For both flats, LECLR2 has the highest energy efficient performance in terms of total yearly energy consumption. In the F and C blocks, it provides, respectively, 40.29% and 41.85% more energy savings than CLR.
- In terms of heating energy savings, LECLR3 is the most efficient unit. It provides heating energy gains during the heating period. In the F and C blocks, it contributes 599.28 and 948.27 kW h, respectively, to the heating energy during the heating period. In terms of total energy consumption, CLR and LECLR3 have the poorest performance due to their high cooling loads.
- Although the smart glazing units (HRBLULE2, HRGRNLE2), composed of glasses with absortive + reflective + low-e coated, are the most efficient units in terms of cooling energy savings, they have poorer performance than LECLR2 in terms of heating energy savings. While in the F block, the total energy consumptions of HRBLULE2 and HRGRNLE2 are 18.68% and 18.85% higher, respectively, than that of LECLR2, in the C block, the total energy consumptions using HRBLULE2 and HRGRNLE2 are 14.49% and 15.12% higher, respectively, than that of LECLR2.
- In comparison to CLR, when LECLR2, HRBLULE2, and HRGRNLE2 are used, 3%, 2%, and 2% heating energy savings, respectively, are provided in Flat 1 of the F block .
- In comparison to CLR, when LECLR2, HRBLULE2, and HRGRNLE2 are used, 7%, 9%, and 9% cooling energy savings, respectively, are provided in Flat 1 of the F block.
- In terms of life cycle costs, HRBLULE2 and HRGRNLE2 are the most economic efficient units. These units have a 3.99% and 3.44% lower life cycle cost, respectively, than LECLR2 in Flat 1 of the F block. LECLR2 is 73% more economic efficient than CLR. These glazing units show the same effect in Flat 1 of the C block.
- HABLU is the third most economic efficient unit in the studied flats. In the F and C blocks, it has a 43.87% and 44.19% lower life cycle cost, respectively, than CLR.
- In terms of the payback period, HABLU is the best alternative, due to its lower initial capital investment in comparison to HRBLULE2, HRGRNLE2, and LECLR2.

Consequently, in terms of energy and economic efficiency, smart glazed units and LECLR2 should be preferred in Trabzon, with a moderate-humid climate, for long-term investments, as opposed to CLR (the existing glazing unit). For different climate regions of Turkey, energy and economy analysis of glazing units will be performed for different orientations and different building shapes in future studies.

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